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Indian Standard

METHODS OF MEASUREMENTS FOR PROPERTIES OF GYROMAGNETIC MATERIALS FOR USE AT MICROWAVE FREQUENCIES

PART II RESONANCE LINEWIDTH

UDC 621·318·134·029·6 : 621·317·4

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July 1978

Indian Standard

METHODS OF MEASUREMENTS FOR PROPERTIES OF GYROMAGNETIC MATERIALS FOR USE AT MICROWAVE FREQUENCIES

PART II RESONANCE LINEWIDTH

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Indian Standard

METHODS OF MEASUREMENTS FOR PROPERTIES OF GYROMAGNETIC MATERIALS FOR USE AT MICROWAVE FREQUENCIES

PART II RESONANCE LINEWIDTH

0. FOREWORD

0.1 This Indian Standard (Part II) was adopted by the Indian Standards Institution on 22 December 1977, after the draft finalized by the Magnetic Components and Ferrite Materials Sectional Committee had been approved by the Electronics and Telecommunication Division Council.

0.2 With the increasing use of ferrites in electronics and telecommunication equipment, and their availability from indigenous manufacturers, it has become necessary to formulate a series of Indian Standards to establish measuring methods for their properties.

0.3 The object of this series of standards is to establish measuring methods for properties of gyromagnetic materials for use at microwave frequencies. The methods described herein do not exclude the use of other methods giving substantially the same or better results and accuracy.

0.4 This standard (Part II) is one of the series of Indian Standards relating to methods of measurements for properties of gyromagnetic materials for use at microwave frequencies. A list of standards of this series is given in Appendix A.

0.5 In preparing this standard, assistance has been derived from IEC Document 51 (C.O.) 164 and 51 (Sectt) 140 'Draft measuring methods for properties of gyromagnetic materials intended for application at microwave frequencies' issued by International Electrotechnical Commission.

0.6 In reporting the result of a test made in accordance with this standard, if the final value, observed or calculated, is to be rounded off, it shall be done in accordance with IS : 2-1960*.

---

*Rules for rounding off numerical values (*revised*).

1. SCOPE

1.1 This standard (Part II) describes method of measurement of gyromagnetic resonance linewidth, ΔH, and effective Lande′ factor, g_{eff}; spin-wave resonance linewidth ΔH_k, and effective resonance linewidth, ΔH_{eff}, of ferrite materials, for application at microwave frequencies.

NOTE 1 — For the purpose of this standard, the words ' ferrite ' and ' microwave ' are used in a broad sense:

- by ' ferrites ' are meant only magnetodielectric chemical components having a spinel crystal structure, but also materials with garnet and hexagonal structures; and
- the ' microwave ' region is taken to include wavelength between 1 m to 1 mm, roughly, the main interest being concentrated on the region 0·3 m to 10 mm.

NOTE 2 — Examples of components employing microwave ferrites are non-reciprocal devices, such as circulators, isolators and non-reciprocal phase shifters. These constitute the major field of application, but the materials may be used in reciprocal devices as well, for example, modulators and (reciprocal) phase-shifters. Other applications include gyromagnetic filters, limitors and more sophisticated devices, such as parametric amplifiers.

2. DEFINITIONS

2.1 For the definitions of general terms used in this standard, reference should be made to IS : 1885 (Part XXXI)-1971*.

SECTION 1 METHOD FOR MEASUREMENTS OF GYROMAGNETIC RESONANCE LINEWIDTH, ΔH, AND EFFECTIVE LANDE′ FACTOR, g_{eff}

3. SCOPE

3.1 This section describes the method for measurements of gyromagnetic resonance linewidth, ΔH, and effective Lande′ factor, g_{eff}, of ferrite materials, for application at microwave frequencies.

4. METHOD OF MEASUREMENT

4.1 Introduction — The gyromagnetic resonance linewidth and the effective Lande′ factor are properties which are necessary for the computation of tensor permeability components. Determination of these quantities involves the measurement of a resonance phenomenon in which both frequency and applied magnetostatic field strength are critical parameters. Stability, both dimensional (of the cavity) and electrical, thus become of primary importance, particularly when it comes to investigating materials having very narrow resonance linewidth, such as monocrystalline ferrite of the garnet type.

---

*Electrotechnical vocabulary: Part XXXI Magnetism.

4.2 Object — To describe a method that can be used for measuring the gyromagnetic resonance linewidth and the effective g-factor of isotropic microwave ferrites over the approximate frequency range 0·3 – 30 GHz. It may be used for materials having wide, as well as, narrow linewidths.

4.3 Theory — The method applies exclusively to the so-called Kittel's mode or the uniform precession resonance; such resonances in which magnetostatic modes are involved or which suffer from ambiguity due to insufficient magnetic saturation are disregarded.

The value of the field for maximum absorption or resonance, H_o, may be theoretically computed in terms of the magnetization of the sample, M_0; the demagnetizing factors, N_x, N_y, N_z; the effective g-factor, g_{eff}, and the measuring frequency, f_o. If the specimen has the shape of a small sphere the relationship reduces to the simple formula:

$$f_o = \frac{\gamma\, \mu_0 H_o}{2\pi}; \qquad N_x = N_y = N_z = 1/3 \qquad \dots\dots\dots (1)$$

If, on the other hand, the specimen is shaped as a disk with a diameter sufficiently larger than the thickness and the external field is perpendicular to the surface; the formula becomes:

$$f_o = \frac{\gamma\, \mu_0\, (\, H_o - M_o\,)}{2\pi}\, ; \qquad N_x = N_y = 0, N_z = 1 \qquad \dots\dots\dots (2)$$

Recognizing that $\gamma = 88\, g_{eff}\, 10^9 T^{-1} S^{-1}$; it is thus possible, knowing f_o, H_0 and M_0, to calculate the effective Lande′ factor g_{eff}.

The gyromagnetic resonance linewidth, ΔH, is (by definition) obtained as the difference between the two magnetic field strength values at which the power absorbed by the ferrite material is one half the maximum absorption.

The method recommended for the measurement of g_{eff} and ΔH is based on the cavity perturbation theory. The absorption at resonance is approximately proportional to the (saturation) magnetization divided by the resonance linewidth. If the absorption becomes too large to maintain the required accuracy, as may sometimes be the case with narrow linewidth materials, the specimen should be reduced in size. To obtain less absorption the diameter (of spherical samples) should be reduced as required (*see* **4.4**).

The absorption in the specimen is measured by determining the change of power incident on the cavity required to keep the output power from the cavity at a fixed reference level.

The variation in input power may be expressed as the variation of the attenuation inserted between the monitored source and the cavity in order to maintain the reference output level. If α_o is the attenuator reading in decibels with no sample present, and α_r is the reading for maximum specimen absorption, then the reading, $\alpha_{1/2}$, corresponding to a specimen absorption of half the resonance value is given by one of the following equations:

$$\alpha_{1/2} = \alpha_o + 10 \log 2 - 10 \log \left(10^{(\alpha_o - \alpha_r) / 10} + 1 \right) \quad \ldots \ldots \ldots (3)$$

or

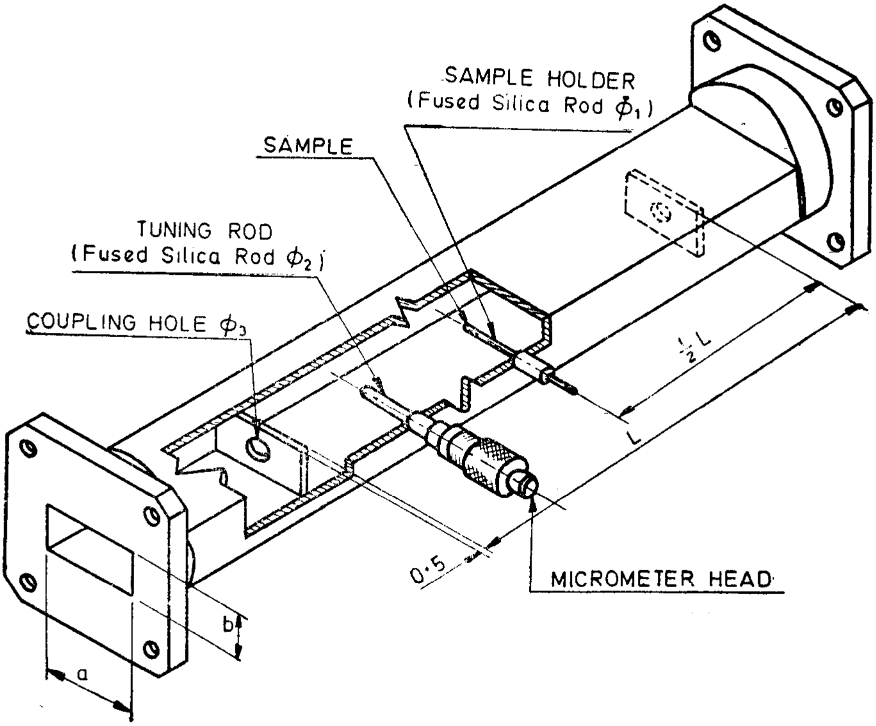
$$\alpha_{1/2} = \alpha_o + 20 \log 2 - 20 \log \left(10^{(\alpha_o - \alpha_r)/20} + 1 \right) \quad \ldots \ldots \ldots (4)$$

The choice of the expression for calculating $\alpha_{1/2}$, is determined by measuring procedure chosen (*see* **4.6**).

4.4 Test Specimens and Cavities — The test specimens for this measurement may be either spherical or disk shaped.

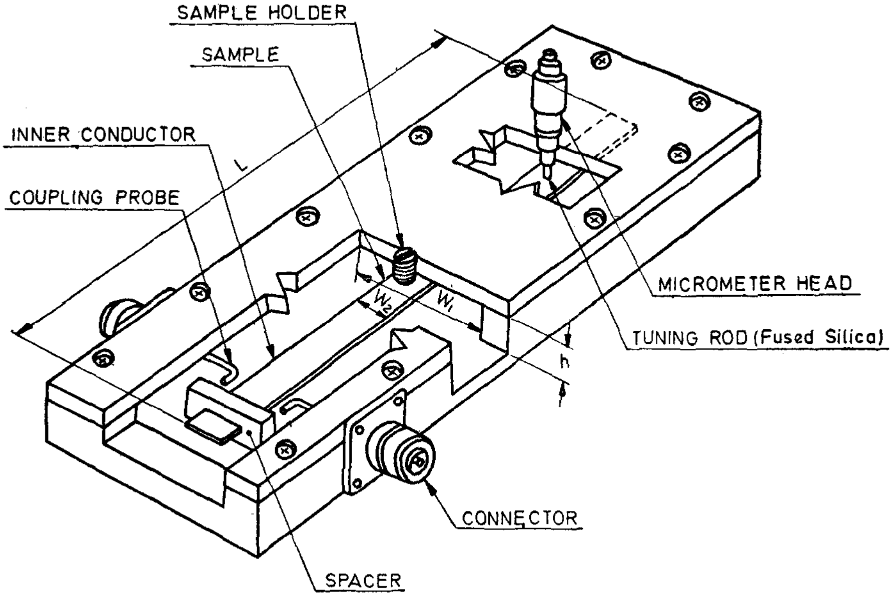
Figure 1 illustrates a cavity of the transmission type, resonant at 10 GHz with a loaded quality factor (Q_o) greater than 2 000. Specimens with a diameter not greater than 1 mm will give sufficient accuracy, provided that ΔH is greater than approximately 800 A/m. When H is less than 800 A/m and particularly when magnetization is high; a smaller sphere will be required. The specimen is positioned at a point of minimum electric and maximum magnetic microwave field. In Fig. 1 the proper specimen position is also indicated. The specimen is mounted on a fused silica (or other dielectric) rod. The hole for inserting the specimen into the cavity is located in the narrow cavity wall and should be not larger than 2·00 mm in diameter (for an X-band cavity). An additional perturbing rod to permit tuning is mounted in a suitable position so as to obtain tuning by interaction with the electric field in the cavity. The input and output lines to the cavity are made to appear as matched loads by means of pads or isolators. This type of cavity design applies for spherical samples over the frequency range of 1 to 30 GHz.

For measurements below 3 GHz, however, a disk-shaped specimen is preferable. The type of cavity recommended in this case is a tunable strip-line resonator with both ends open-circuited as illustrated in Fig. 2. As is evident from the figure the cavity has odd-order resonances at wavelengths of about $2L$, $2/3L$,....where L is the length of the strip-line inner conductor. The specimen is glued to the inner surface of the outer conductor in the vicinity of the centre of the inner conductor. To keep the microwave field as uniform as possible over the specimen, the sample diameter should be less than one-third of the width of the inner conductor. The tuning rod serves to tune the cavity by additional perturbation so that measurement may be made at a predetermined frequency.



Dimension (mm)	*Frequency* (GHz)		
	3	10	30
L	278	118·4	36·9
a	72·14	22·86	8·636
b	34·04	10·16	4·318
ϕ_1	2	1	0·5
ϕ_2	6	3	1·5
ϕ_3	15	5	2·5

FIG. 1 CAVITY FOR MEASUREMENT OF GYROMAGNETIC RESONANCE LINEWIDTH AND EFFECTIVE LANDE′ FACTOR



Dimension (mm)	*Frequency* (MHz)	
	300	1 000
L	500	150
W_1	60	60
W_2	20	20
h	7	7

FIG. 2 STRIP-LINE RESONATOR FOR MEASUREMENT OF GYROMAGNETIC RESONANCE LINEWIDTH AND EFFECTIVE LANDE′ FACTOR AT LOW FREQUENCY

4.5 Measuring Apparatus — Figure 3 is a schematic diagram of the equipment required to make the measurements. Power from a suitable microwave source *A*, operated either unmodulated or with amplitude modulation, but free of frequency modulation, is fed through a precision variable attenuator *F*, to the cavity *G*, and the output power is detected and indicated on a suitable meter *H*. The power incident on the precision attenuator is monitored at *E*, by means of a directional coupler and crystal detector, and this incident power is kept constant throughout the measurement by means of a variable attenuator *C*. The microwave frequency, which is monitored at *B*, may be kept unchanged because the perturbing rod may be used to tune the cavity to the generator frequency. An adjustable magnetic field of sufficient stability perpendicular to the microwave magnetic field is applied to the specimen. The non-homogeneity of the applied field over the specimen shall be negligible compared to the linewidth being measured.

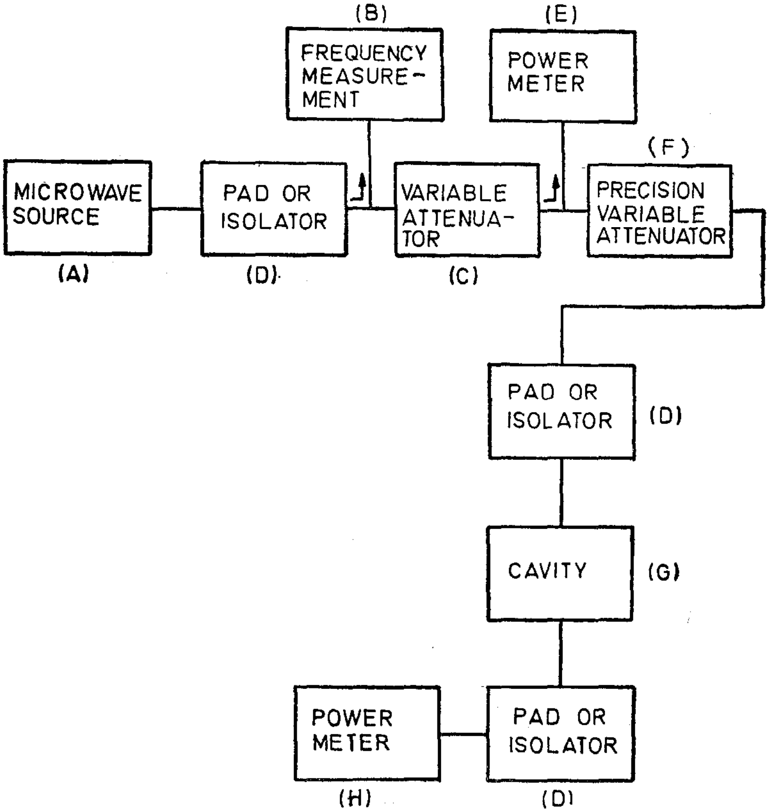


FIG. 3 SCHEMATIC DIAGRAM OF EQUIPMENT REQUIRED FOR MEASUREMENT OF GYROMAGNETIC RESONANCE LINEWIDTH AND EFFECTIVE LANDE' FACTOR

4.6 Measuring Procedure — Set the generator frequency as closely as possible to the measuring frequency. Tune the cavity for maximum transmission with the aid of the dielectric rod. Establish an input level measured at E, a setting, α_0 on the precision attenuator, and an output level measured at H. Take this output level as a reference value. Insert the specimen into the cavity. This operation should have negligible effect on the output level. Apply the magnetic field and adjust it for maximum absorption (minimum transmission). Determine the new setting α_r on the precision attenuator which restores the output level to the reference value. Determine the microwave frequency f_0, and the applied magnetostatic field strength H_0.

The gyromagnetic resonance linewidth may now be obtained by two slightly different methods.

4.6.1 *Method A* — Calculate the attenuator setting to obtain the reference output level at the half-power points with the aid of equation (3). Set the precision attenuator at this value and vary the magnetic field, noting the two magnetic field strengths at which the reference output level is obtained H_1 and H_2.

4.6.2 *Method B* — Calculate the attenuator setting to obtain the reference output level at the half-power points with the aid of equation (4). Set the precision attenuator at this value and vary the magnetic field to obtain the reference output level. Retune the cavity for maximum output with the aid of the dielectric rod. Read just the field strength and the tuning as required and note the final field strength value H_1. Repeat the procedure at the other half-power point to obtain H_2.

In order to check sphericity and isotropy of spherical specimens, the specimen may be rotated in the cavity. The values obtained for H_0 and ΔH should not depend upon the specimen orientation for correctly shaped isotropic materials. Allowable limits of variation are 1 percent in H and 5 percent in ΔH. For thin disk specimens the effect of the electromagnetic mirror image upon the measured data should be eliminated prior to final measurement. This is effectively accomplished by making successive measurements on a specimen whose thickness is varied stepwise by means of careful grinding. The values obtained for H_0 and ΔH should not depend upon the thickness. Allowable limits of variation are in this case 3 percent in H_0 and 5 percent in ΔH.

4.7 Calculation — The effective Lande′ factor is calculated from observed values of frequency and resonance field strength according to equation (1) (sphere) or equation (2) (disk).

The gyromagnetic resonance linewidth is calculated as:

$$\Delta H = | H_1 - H_2 | \qquad \ldots \quad \ldots \quad \ldots \quad \ldots (5)$$

regardless of whether Method A or Method B is used for the measuring procedure.

4.8 Accuracy — If frequency is measured with an accuracy of ±1 percent and magnetic field strength with an accuracy of ±2 percent, the relative errors in the determination of ΔH and g_{eff} become equal to ±5 percent and ±2 percent, respectively.

4.9 Data Presentation — Data should be presented so as to conform with the requirements of IS : 8454-1977*. It should be pointed out that the values refer to a particular measuring frequency. This may be done by using a subscript which represents the measuring frequency in GHz, that is, ΔH_{10}, g_{10} (if measured at 10 GHz), in the following manner:

a) Resonance linewidth at 10 GHz, ΔH_{10}, at a temperature of θ°C; XYZ kAm^{-1} ±5 percent, and

b) Effective Lande' factor at 10 GHz, g_{10}, at a temperature of θ°C; XYZ ±2 percent.

SECTION 2 METHOD FOR MEASUREMENT OF SPIN-WAVE RESONANCE LINEWIDTH, ΔH_k

5. SCOPE

5.1 This section describes the method for measurement of spin-wave resonance linewidth, ΔH_k, of ferrite materials, for application at microwave frequencies.

6. METHOD OF MEASUREMENT

6.1 Introduction — Ferrite materials exhibit an anomalous absorption at high rf power levels that results from a power dependent coupling between the uniform mode of precession and spin waves. Through this transfer of energy certain spin wave amplitudes build up. The spin wave frequencies are equal to one half the applied frequency or the applied frequency. The absorption is observed when the spin waves are parametrically excited beyond some threshold level where unstable growth of spin wave amplitude occurs. This threshold level, and hence the relative high power performance of the ferrite material, may be shown to be proportional to the spin-wave linewidth of the material.

Spin-wave linewidth is an intrinsic property of the material, and its determination is necessary to characterise the material completely. Not only do the high power characteristics of the materials depend on ΔH_k, but this intrinsic linewidth is also indicative of loss in applications where the materials is biased far from resonance as in most phase shifters and circulator designs where no low to medium k spin waves are degenerated with the operating frequency.

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*Guide for drafting of performance specifications for gyromagnetic materials for use at microwave frequencies.

6.2 Object — To describe the procedure for the determination of the microwave spin-wave linewidth of nonmetallic magnetic materials. The test is made at X-band frequencies, on spherical samples at room temperature. Both monocrystalline and polycrystalline samples may be measured by this procedure.

The measurement described here is based on the so-called parallel pump technique wherein the sample is biased below resonance by a magnetostatic field applied parallel to the rf field. In this arrangement the sample shows low magnetic loss at low rf power levels. The threshold rf field is determined by observing the onset of nonlinear loss as evidenced by a change in shape of the rf pulse.

6.3 Theory — The excitation of spin waves beyond the threshold level is observed either as an increase in loss at magnetostatic field values below that required for resonance or as a saturation and broadening of the main resonance line. These effects are indicated in Fig. 4. Because the subsidiary resonance exhibits a more sharply defined threshold, more accurate measurements of threshold level are possible in that region.

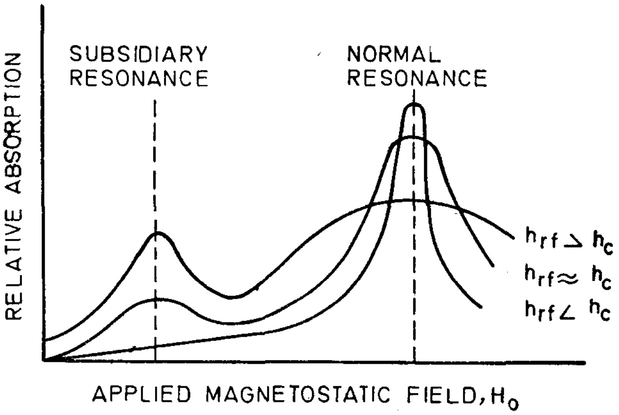


FIG. 4 SUBSIDIARY ABSORPTION AND SATURATION OF THE NORMAL RESONANCE

With increasing rf field, high power absorption is first observed at the trailing edge of the rf pulse. As the rf field is increased beyond threshold this absorption occurs over increasingly larger fractions of the pulse as indicated in Fig. 5.

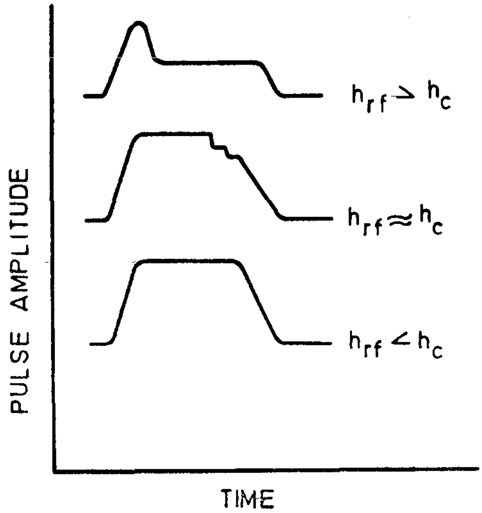


FIG. 5 PULSE DETERIORATION AT ONSET OF SUBSIDIARY RESONANCE

This behaviour is a result of the time required for the spin-wave amplitude to build up and can lead to some ambiguity in critical field determination. It is experimentally found that measured critical field values are a function of T_p, where T_p is the pulse duration. Optimally, the measurements should be made with a pulse length long compared to the time required for spin-wave build-up at threshold. (For polycrystalline materials with $\Delta H_k > 800\ \mathrm{Am}^{-1}$ a pulse length of 1 μs is adequate). Equipment limitations may make this impossible, and as an alternative, measurements may be made at different pulse lengths and extrapolated as indicated in Fig. 6 to obtain the true value.

The threshold field value, h_c is equal to the rf magnetic field strength at the sample at the critical power level. When the sample is located at the centre of a TE_{10n} (where n is even) cavity the rf field strength is given by:

$$h = 4\sqrt{\frac{P_{in} \cdot Q_L}{\left(1 + \gamma_1\right)\mu_0 \pi f_0 \cdot abd\left[1 + \left(\frac{d}{na}\right)^2\right]}} \qquad \dots\ \dots\ \dots\ (6)$$

where

γ_1 = input VSWR of cavity at resonance;

P_{in} = peak power incident upon the cavity;

Q_L = loaded Q of the cavity;
a, b, d = cavity width, height and length, respectively;
f_o = resonant frequency of the cavity;
μ_o = the magnetic constant; and
n = number of half wavelengths along the cavity.

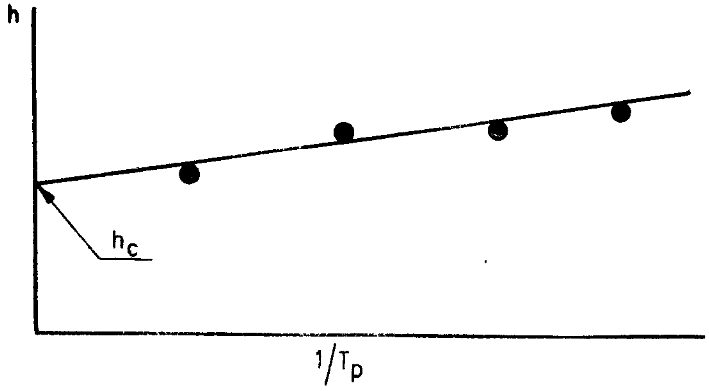


FIG. 6 MEASURED CRITICAL FIELD VALUE AS A FUNCTION OF PULSE DURATION

From this threshold field value the spin-wave linewidth ΔH_k, in the general case may be calculated from the formula:

$$\Delta H_k = h_c \cdot \frac{\omega_m}{\omega} \cdot \sin^2 \theta_k \qquad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \qquad (7)$$

The lowest value of h_c is obtained when $\theta_k = \pi/2$, in which case:

$$\Delta H_k = h_c \cdot \frac{\omega_m}{\omega} \qquad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \qquad (8)$$

where

$\omega_m = \gamma \mu_o M_s$
ω = operating angular frequency.

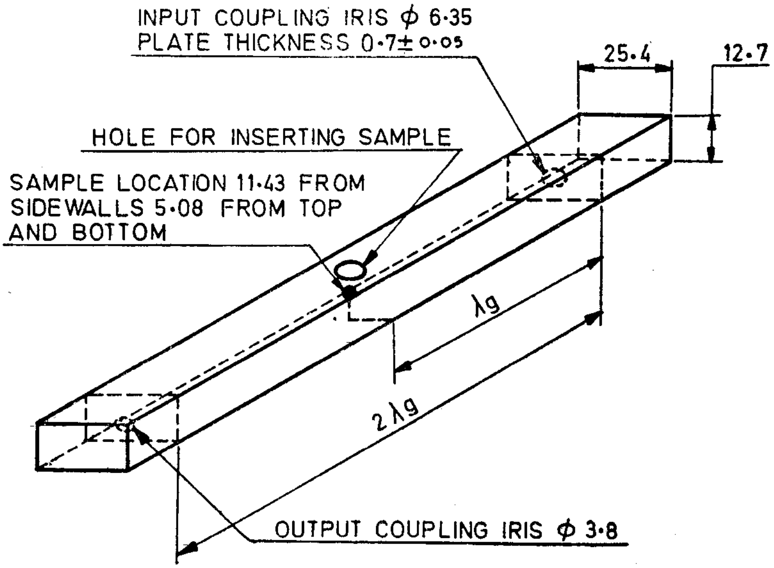
The minimum threshold for parallel pumping occurs when spin waves with $\theta_k = \pi/2$ are degenerate with one half the operating frequency, and in the case of a sphere this occurs at a magnetic field strength. H_o given by:

$$H_o = -\frac{M_s}{6} + \frac{1}{2}\sqrt{M_s^2 + \left(\frac{\omega}{\gamma \mu_o}\right)^2} \qquad \dots \quad \dots \quad \dots \qquad (9)$$

where

M_s = saturation magnetization.

6.4 Test Specimen and Cavity — The sample to be measured should be spherical in shape with a diameter between 1 and 2 mm. A transmission cavity of the type sketched in Fig. 7 may be conveniently used as a TE_{104} cavity resonant between 9 and 10 GHz with a loaded Q greater than 2 000. The sample is positioned in the centre of the cavity cross-section at a point of minimum microwave electric field and maximum microwave magnetic field. The sample is mounted on a fused silica or other dielectric rod. The hole for inserting the sample into the cavity is centered in the broad wall of the cavity.


INPUT COUPLING IRIS ϕ 6·35
PLATE THICKNESS 0·7±0·05
25·4
12·7
HOLE FOR INSERTING SAMPLE
SAMPLE LOCATION 11·43 FROM SIDEWALLS 5·08 FROM TOP AND BOTTOM
λg
2λg
OUTPUT COUPLING IRIS ϕ 3·8

All dimensions in millimetres.

Fig. 7 Typical TE$_{104}$ Cavity for the Measurement of Spin-Wave Linewidth at 9 300 MHz

6.5 Measuring Apparatus — Figure 8 is a block diagram of the equipment required to make these measurements. The pulse modulator *A* operates the magnetron *B* at a duty cycle of about 0·001 and provides a synchronizing pulse to the oscilloscope *L*. The isolator *C* provides a matched impedance to the magnetron, and the power divider *D* allows the power to the test cavity *F* to be varied over at least a 20 dB range. The unused power is dissipated in the high power termination *E*. The frequency and power level incident on the test cavity are monitored by the frequency motor *H* and the power meter *I*. This monitoring is accomplished with a 30 dB directional coupler whose directivity exceeds 40 dB. The power reflected from the cavity at resonance is monitored through an identical coupler by the power meter *G*. By comparing the reading of meter *G* and *I* the power reflection coefficient, *r*, may be obtained and the input VSWR, γ_1 computed. The transmitted signal is terminated in a high power termination *J* and sampled through a 30 dB directional coupler by a crystal detector *K*. The output of the crystal detector *K* is displayed on the oscilloscope *L*.

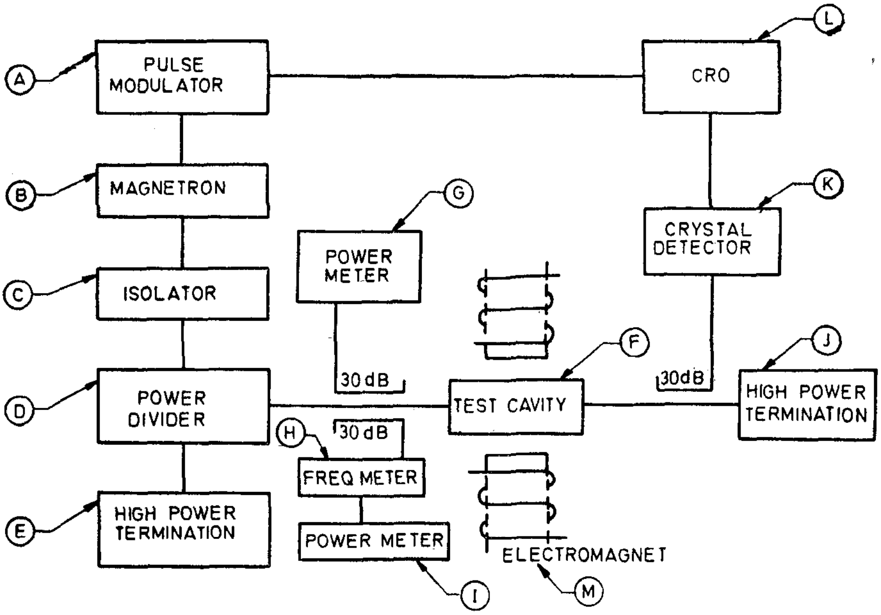


FIG. 8 BLOCK DIAGRAM OF SPIN-WAVE LINEWIDTH TEST EQUIPMENT

6.6 Calibration — The loaded *Q* of the cavity shall be determined. This may be easily accomplished with the equipment and procedures used to determine the complex dielectric constant of ferrite materials.

6.7 Measuring Procedure — The sample to be measured is mounted in the cavity, and the field supply by the electromagnet *M* is adjusted to provide a magnetostatic field strength approximately equal to that calculated from equation (9). This field should be oriented in a plane parallel to the broad wall of the waveguide and normal to the longitudinal axis of the guide, that is, parallel to the rf magnetic field in the guide at the sample location.

The frequency of the magnetron is made to coincide with the resonant frequency of the cavity by adjusting the frequency for maximum output of the crystal detector *K*. The pulse duration should be made as long as possible, and the repetition rate adjusted to yield a duty cycle of the order of 0·001. With the magnetron operating at the resonant frequency of the cavity, the power reflection coefficient may be determined from reading at meters *G* and *I*.

The power divider is adjusted so that the rf magnetic field in the cavity according to equation (6) is well below the critical value and then increased until some deterioration of pulse shape is observed. The magnetostatic field is then carefully adjusted about the determined value H_0, to minimize the critical field strength. The incident power level that first causes a perceptible degradation in shape of the trailing edge of the pulse may then be used to calculate the critical rf power level for that pulse length.

The measurement should be repeated for shorter pulse lengths to establish a basis for extrapolation to h_c as indicated by Fig. 6. For materials with $\Delta H_k > 800$ Am^{-1}, a pulse length of 1/μs is sufficiently long to make extrapolation unnecessary.

6.8 Calculation — From the extrapolated value of h_c the spin-wave linewidth, ΔH_k, is calculated from equation (8).

6.9 Accuracy — Cavity *Q* determination should be made to an accuracy of ±3 percent. Incident power level determination should be made to an accuracy of ±10 percent. Cavity dimensions and resonant frequency measurements are easily made to be within ±0·5 percent. This restricts the expected error in ΔH_k to ±15 percent.

6.10 Data Presentation — Value of ΔH_k determined from extrapolated value of h_c should be reported. The frequency of measurement, temperature at which measurements were made, and unique identity of sample should also be reported.

SECTION 3 METHOD FOR MEASUREMENT OF EFFECTIVE RESONANCE LINEWIDTH, ΔH_{eff}

7. SCOPE

7.1 This section describes the method for measurement of effective resonance linewidth, ΔH_{eff}, of ferrite materials for application at microwave frequencies.

8. METHOD OF MEASUREMENT

8.1 Introduction — At magnetostatic field strengths widely different from that required for resonance at the working frequency, calculation of the imaginary parts of the permeability tensor components using the gyromagnetic resonance linewidth, H, yields results which can be grossly in error. Consequently, insertion loss values cannot be predicated with sufficient accuracy. In order to eliminate this difficulty an effective resonance linewidth, ΔH_{eff} is defined, which takes into account any deviations from the classical Lorentzian behaviour.

8.2 Object — This method covers the measurement of the magnetic permeability tensor components, wherefrom the effective resonance linewidth is deduced. The method is valid for polycrystalline isotropic ferrites operating at microwave frequencies, outside the gyromagnetic resonance region and at low power level. The test specimen is a rod, coaxially arranged in a resonant cylindrical cavity, and is submitted to an axial magnetostatic field. The effective resonance linewidth is a useful parameter as regards insertion losses of microwave devices.

In this context, effective resonance linewidth means the relaxation parameter, W. Formal calculation of μ''_+ also requires knowledge of the frequency shift, S.

8.3 Theory

8.3.1 *Definitions* — In an isotropic magnetic medium submitted to a static magnetic field, H_0, the microwave magnetic flux density is related to the microwave magnetic field strength by:

$$b = \mu_o (\mu) h = \mu_0 (1 + X) h \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (10)$$

where

μ_o = permeability of free space,
(μ) = relative tenser permeability of the medium, and
(X) = relative tenser susceptibility of the medium.

(μ) and (X) are functions of H_0.

In perpendicular pumping, the susceptibility tenser may be reduced to a two-dimensional expression:

$$(X) = \left\{ \begin{matrix} X_+ & O \\ O & X_- \end{matrix} \right\} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (11)$$

where X_+ and X_- are the susceptibilities for the clockwise and counter-clockwise circularly polarized waves, respectively. They normally are complex quantities:

$$X_{\pm} = X'_{\pm} - j X''_{\pm} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (12)$$

The imaginary part $X'_{\pm}$ initiating the magnetic losses in the medium, through the effective resonance linewidth ΔH_{eff}:

$$H_{\text{eff}} = 2\ M_s\ .\ Im\left(\frac{1}{X_+}\right) \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (13)$$

where M_s is the saturation magnetization.

But these susceptibilities $X_{\pm}$ are intrinsic susceptibilities of the medium. Due to demagnetizing effects the quantities obtained through measurement in a cavity are effective susceptibilities:

$$X_{\pm e} = X'_{\pm e} - jx''_{\pm e} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (14)$$

H_{eff} may then be rewritten:

$$H_{\text{eff}} = 2\ M_s \cdot Im\left(\frac{1}{X_{+e}}\right) = 2\ M_s \frac{X''_{+e}}{(X'_{+e})^2 + (X''_{+e})^2} \quad \ldots \quad \ldots \quad (15)$$

8.3.2 *Measurement* — A cylindrical TM_{110} resonator and a rod-shaped specimen are used for the measurement. Quantities that shall be measured are, at the applied magnetic field H_o and for the clockwise sense of circular polarization, the resonance frequency of the cavity with and without the sample, the loaded Q of the cavity with and without the specimen and the cavity and specimen dimensions. The loaded Q of the empty cavity is checked by inserting a low loss magnetic sample saturated above 1 MAm^{-1}. The method is not suitable for materials with dissipation factors:

$$\frac{X''_+}{1 + X'_+} > 0{\cdot}1$$

If f_o is the resonance frequency of the empty cavity and $f = f_o + \delta f_{+e}$ that of the cavity containing the specimen, X'_{+e} and X''_{+e} may be expressed as functions of $\delta f_+/f_o$ by an approximation.

With the cavity dimensions given in Fig. 9B, the susceptibility components are given by:

$$\frac{1}{1 + X'_{+e}} = 3{\cdot}671\ \varepsilon'\ C_1 - 1 + 2\left(\frac{1 + 5{\cdot}485\ \dfrac{\delta f_+}{f_o}\ \log 3{\cdot}415\ \dfrac{b}{a}}{C_4{}^{1\ 2}}\right) \ldots (16)$$

$$\frac{X''_{+e}}{(1 + X'_{+e})^2} + 3{\cdot}671\ \varepsilon''\ C_1$$

$$= 2\left(\frac{1}{Q_+} - \frac{1}{Q_1}\right)\left(\frac{1}{6{\cdot}153\ C_1\ C_4} + 3{\cdot}671\ C_1C_2 + C_3\right) \quad \ldots \quad (17)$$

$$Q_1 = Q_o\left(1 + \frac{\delta f}{f_o}\right)^{\frac{1}{2}} \frac{1 + 3{\cdot}671\ C_1\ C_2 + C_3}{C_4{}^2} + 1{\cdot}957\ C_1C_2 + C_3 \ldots (18)$$

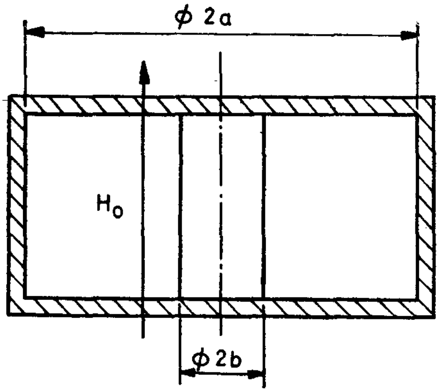


FIG. 9A SECTIONAL VIEW OF THE CAVITY WITH SPECIMEN

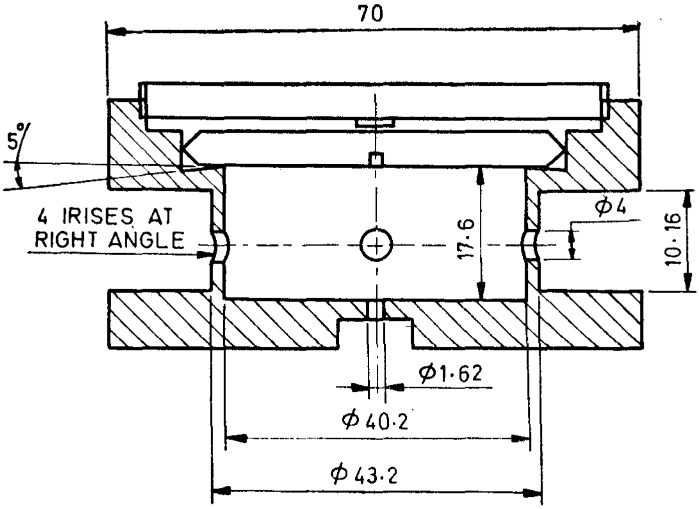


FIG. 9B DIMENSIONS OF CAVITY DESIGNED FOR RESONANCE AT A FREQUENCY OF 0·1 GHz

where

ε' = real part of the relative permittivity of the medium;
b = radius of the specimen (*see* Fig. 9A);
a = radius of the cavity, determined from the resonance frequency of the empty cavity (*see* Fig. 9A);
ε'' = imaginary part of the relative permittivity of the medium;

Q_+ = loaded Q of the cavity with real sample;

Q_1 = loaded Q of the cavity with an ideal lossless sample, having the real parts of the susceptibility as the measured one;

Q_o = loaded Q of the empty cavity;

$$C_1 = \left(\frac{b}{a}\right)^2 \left(1 + \frac{2\delta f_+}{f_o}\right);$$

$$C_2 = \frac{\varepsilon'}{2}\left(1 + \frac{1}{1 + X'_{+e}}\right) - 1;$$

$$C_3 = \frac{1}{4}\left(1 - \frac{1}{(1 + X'_{+e})^2}\right); \text{ and}$$

$$C_4 = \left[1 - 1{\cdot}191\,\frac{\delta f_+}{f_o}\left(\frac{1}{3{\cdot}761\ C_1} + 1 - 4{\cdot}605 \log 3{\cdot}415\,\frac{b}{a}\right)\right]^2.$$

10.4 Test Specimen and Cavity — The specimen shall be cylindrical of diameter 1·60 ± 0·01 mm and of length 22 ± 0·5 mm. It shall be in a satisfactory clean and dry state. The test specimen is inserted in the cylindrical TM_{110} cavity. The ends of the specimen shall pass through holes in the cavity wall, the hole diameter being 1·62 ± 0·01 mm. A uniform axial magnetic field is imposed on the specimen.

The cylindrical TM_{110} cavity has its dimensions given by Fig. 9B. It presents four irises at right angles, two of them for excitation of the circularly polarized wave, the two other ones for detection of that same wave. The coupling hole diameter is 4 mm. The coupling coefficient is identical for each iris and smaller than 0·01. The loaded Q of the cavity shall be greater than 5 000.

10.5 Measuring Apparatus — Figure 10 is a schematic diagram of the equipment required for the measurement. Power from a suitable CW generator G with a frequency stability better than 10^{-7} is run through a variable attenuator A, the frequency being measured in F, then through a variable precision attenuator V, power being measured at P. A magic tee divides the power in two parts which through adjustments of the variable attenuator A_1 and the variable phase shifter D_1 recombine to give a circularly polarized wave inside the cavity C.

The two output irises feed through adjustments of the variable attenuator A_2 and the variable phase shifter D_2 a magic tee delivering output powers leading to X_{+e} or X_{-e} ; a_1, a_2 are fixed complementary attenuators, d_1 and d_2 fixed complementary phase shifters, I isolators. The axial static magnetic field H_o, is measured with a field strength meter M.

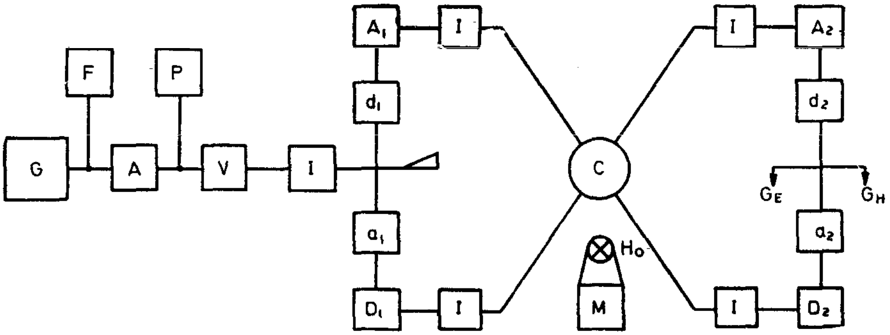


FIG. 10 SCHEMATIC DIAGRAM OF EQUIPMENT

10.6 Calibration — The frequency meter, the variable precision attenuator and the field strength meter shall be calibrated.

10.7 Measuring Procedure

10.7.1 *Equipment Adjustment* — Insert a low loss magnetic sample and apply a magnetostatic field of about 40 kAm^{-1} in order to remove the cavity degeneracy.

With any setting of A_1 and D_1 shift the frequency to obtain on G_H a maximum output, for the upper resonance frequency corresponding to the clockwise circular mode. Adjust A_2 and D_2 to obtain on G_E a minimum output corresponding to a minimum detection of the counter clockwise circular mode.

Shift the frequency down to the lower resonance frequency corresponding to the counter clockwise circular mode. Adjust A_1 and D_1 to obtain a minimum detection on G_E. The counter clockwise mode is then no longer exciting the cavity.

With the cavity so adjusted remove the sample.

Measurements are performed only on G_H for the clockwise circular mode.

10.7.2 *Measurement Procedure* — Without the specimen in the cavity introduce an attenuation of 3 dB with the variable precision attenuator V. Adjust the microwave frequency to cavity resonance as indicated by maximum power output with respect-to-frequency variation. Note the indication of the output power level at G_H and measure the resonance frequency f_0, with the frequency meter F. Remove the 3 dB of attenuation on V and locate the two frequencies at which the output power is the same as at cavity resonance with the 3 dB attenuation in. The frequency separation of the half power points is measured on the frequency meter F as $f_{\frac{1}{2}}$. The loaded Q of the empty cavity is given by:

$$Q_o = \frac{f}{\Delta f_{\frac{1}{2}}}$$

Check by inserting the low-loss sample saturated above 1 MAm^{-1}.

Insert the specimen into the cavity and measure in the same way f_+ and Q_+ at the selected magnetostatic field strength.

10.8 Calculation — ε' and ε'' being deduced from a dielectric measurement in a TM 010 cavity X'_{+e}, X''_{+e} and ΔH_{eff} are calculated from the equations (15), (16), (17) and (18).

10.9 Accuracy — The overall accuracy in X'_{+e} is 2 percent. The overall accuracy in X''_{+e} is given by the following curve.

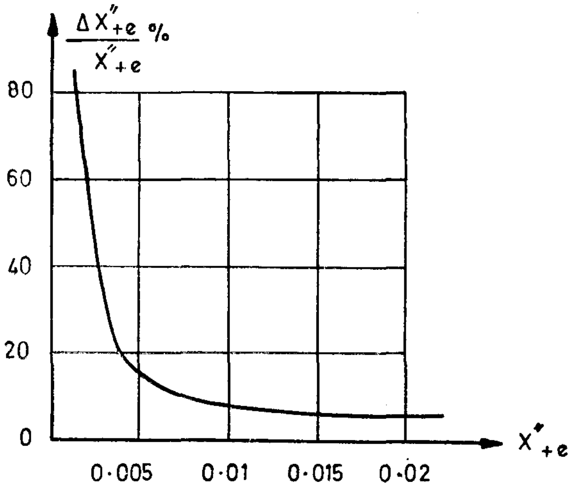


FIG. 11 ACCURACY IN X''_{+e}

10.10 Data Presentation — The report shall include the following:

a) Unique identity of the specimen;
b) Value of the magnetic field strength H_o;
c) Values of X'_{+e}, X''_{+e} and ΔH_{eff}; and
d) Temperature of the sample during the measurement.

APPENDIX A

(*Clause* 0.4)

IS : 8426 Methods of measurements for properties of gyromagnetic materials for use at microwave frequencies:

Part I Magnetization

- Section 1 Saturation magnetization, M_s
- Section 2 Magnetization (at specified field strength), M_H

Part II Resonance linewidth

- Section 1 Gyromagnetic resonance linewidth, ΔH and effective Lande′ factor, g_{eff} (general)
- Section 2 Spin-wave resonance linewidth, ΔH_k
- Section 3 Effective resonance linewidth, ΔH_{eff}

Part III Permittivity, apparent density and Curie temperature

- Section 1 Complex permittivity, ε_r
- Section 2 Apparent density, ρ_{app}
- Section 3 Curie temperature, θ_c